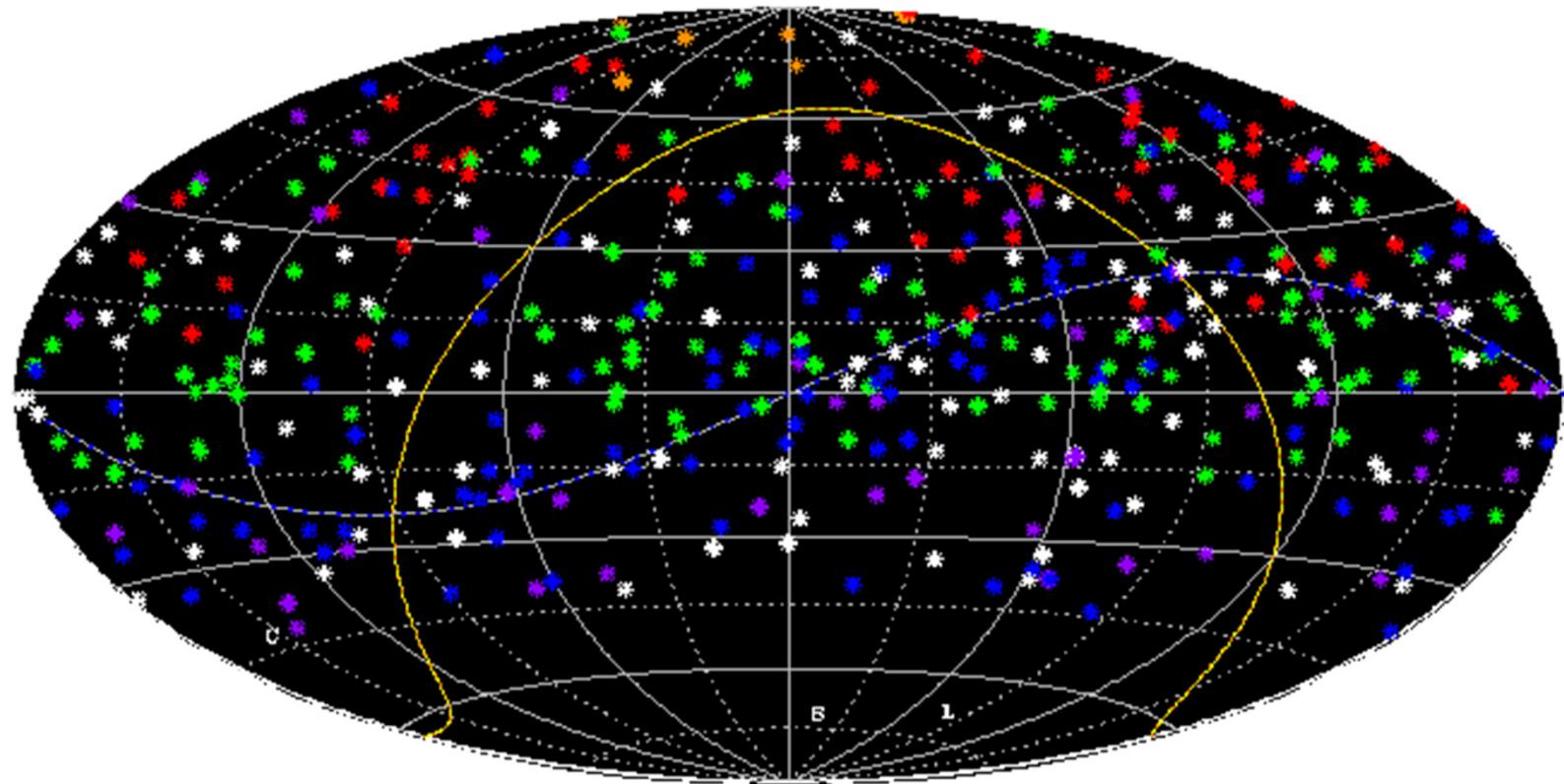




# EVGA 2011, Bonn, Germany



## The Celestial Frame at X/Ka-band (8.4/32 GHz)



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Jet Propulsion Laboratory, Caltech/NASA

J.E. Clark, C. Garcia-Miro, S. Horiuchi, L.J. Skjerve, O.J. Sovers

*30 March 2011*



# Overvie



## W

- Status of current radio-based celestial frames
  - ICRF2: wavelength 3.6cm, 3.4K objects, 40-100  $\mu$ as
  - K-band: wavelength 1.2cm, 0.3K objects, 100-250  $\mu$ as
  - X/Ka: wavelength 9mm, 0.5K objects, 200-300  $\mu$ as
- Need southern stations: **complementary geometry**
  - Benefits southern cap, Declination accuracy
- Gaia/optical to VLBI/radio frame tie  
70-100  $\mu$ as independent accuracy verification per source  
5- 15  $\mu$ as potential precision in 3-D frame tie



# Celestial Frame Collaborators



- ICRF2 Working Group (S/X-band, 3.6cm)

C. Ma chair

E.F. Arias, G. Bianco, D.A. Boboltz, S.L. Bolotin, P. Charlot, G. Engelhardt, A.L. Fey,  
R.A. Gaume, A.-M. Gontier, R. Heinkelmann, C.S. Jacobs, S. Kurdubov, S.B. Lambert,  
Z.M. Malkin, A. Nothnagel, L. Petrov, E. Skurikhina, J.R. Sokolova, J. Souchay, O.J. Sovers,  
V. Tesmer, O.A. Titov, G. Wang, V.E. Zharov, C. Barache, S. Bockmann, A. Collioud,  
J.M. Gipson, D. Gordon, S.O. Lytvyn , D.S. MacMillan, R. Ojha

- KQ Collaboration (1.2cm, 7mm or 24, 43 GHz)

G.E. Lanyi, P.I.

D.A. Boboltz, P. Charlot, A.L. Fey, E. B. Fomalont, B.J. Geldzahler, D. Gordon,  
C.S. Jacobs, C. Ma, C.J. Naudet, J.D. Romney, O.J. Sovers, L.D. Zhang

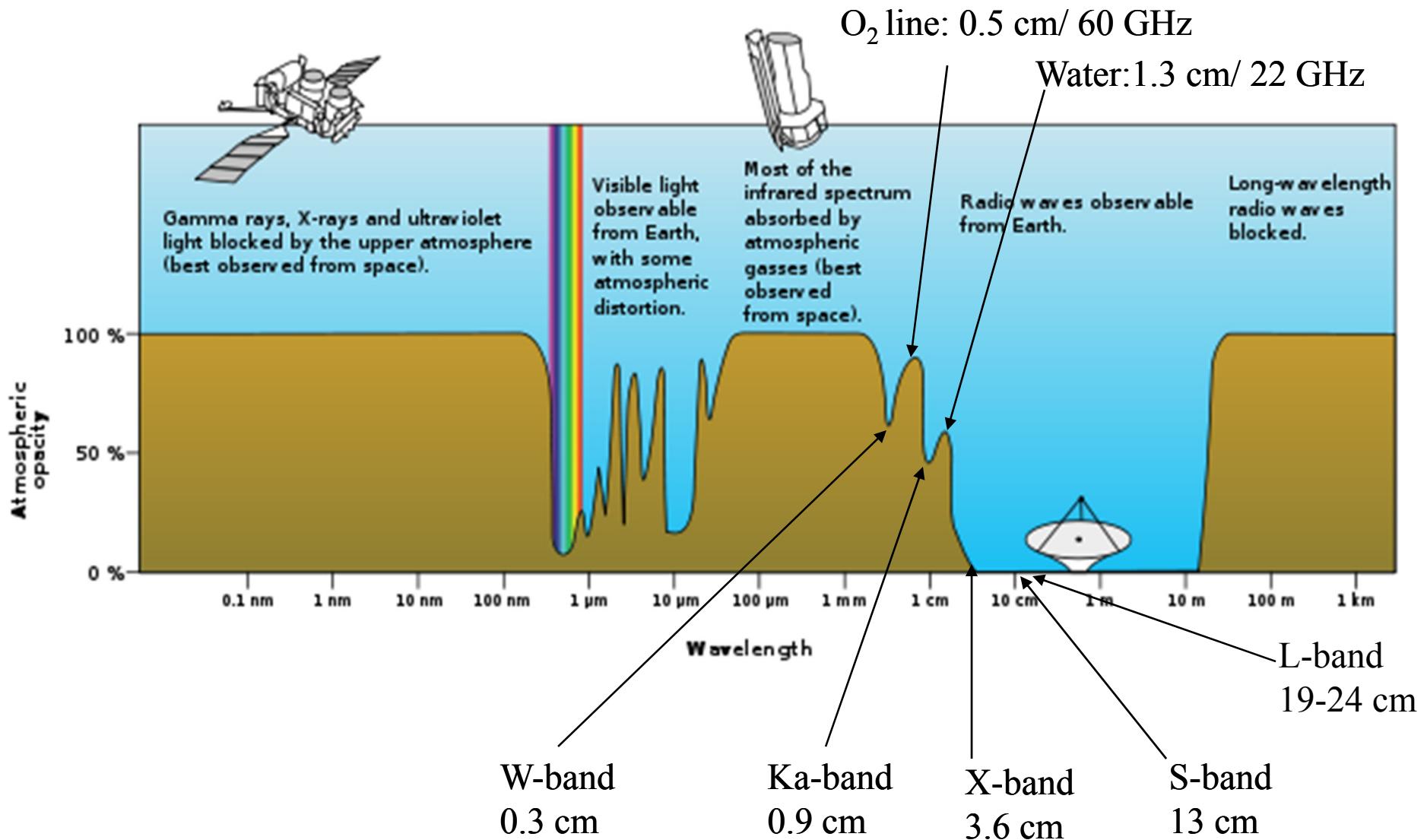
- X/Ka-band Collaboration (9mm, 32 GHz)

C.S. Jacobs, P.I.

J. Clark, C. Garcia-Miro, S. Horiuchi, V.E. Moll, L.J. Skjerve, O.J. Sovers



# Why observe in Radio? The ‘Window’





# Current Status of Celestial Reference Frames at radio wavelengths:

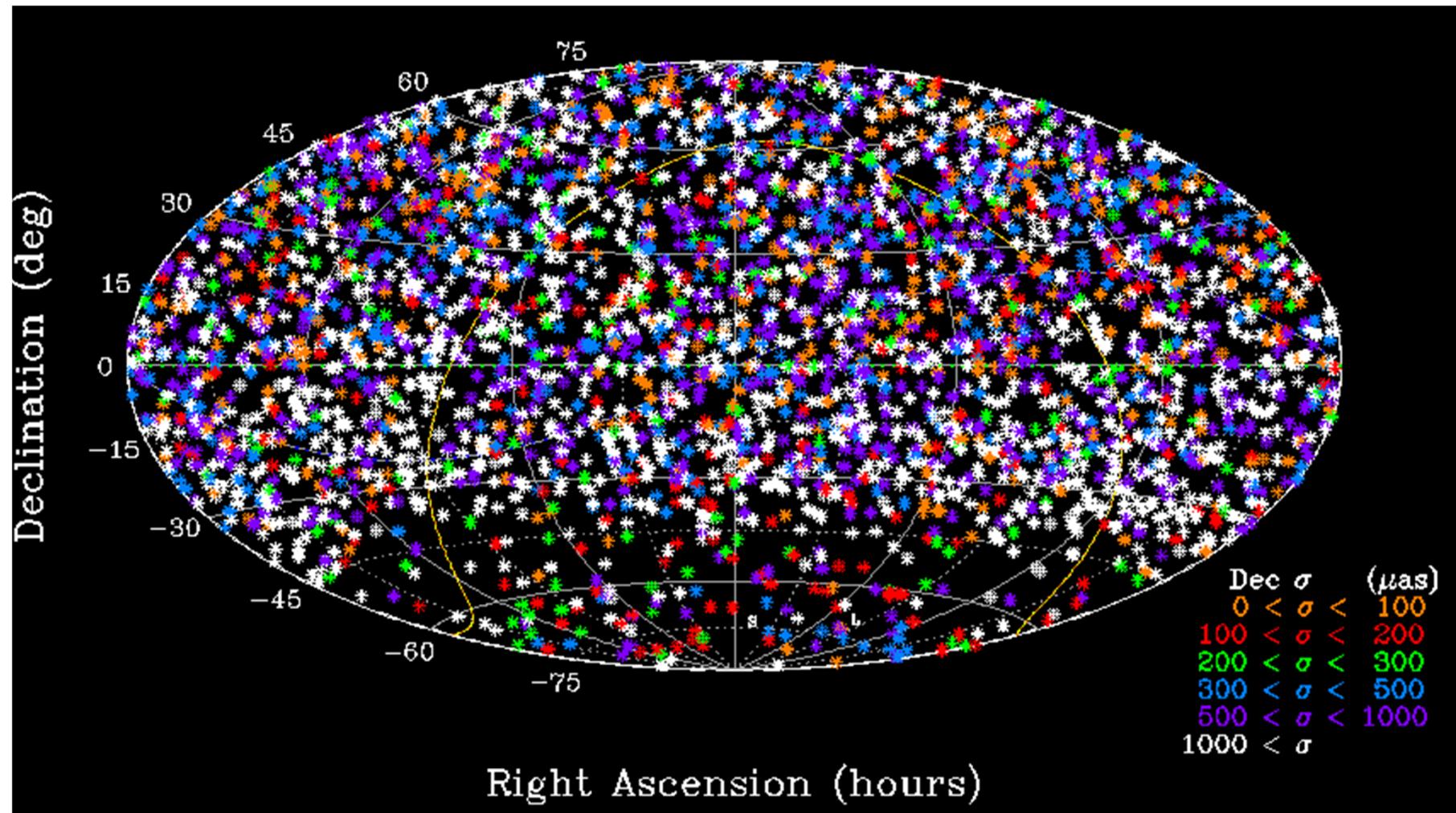
**S/X ICRF2:** 3.6cm, 8 GHz

**K-band:** 1.2cm, 24 GHz

**X/Ka-band:** 9mm, 32 GHz



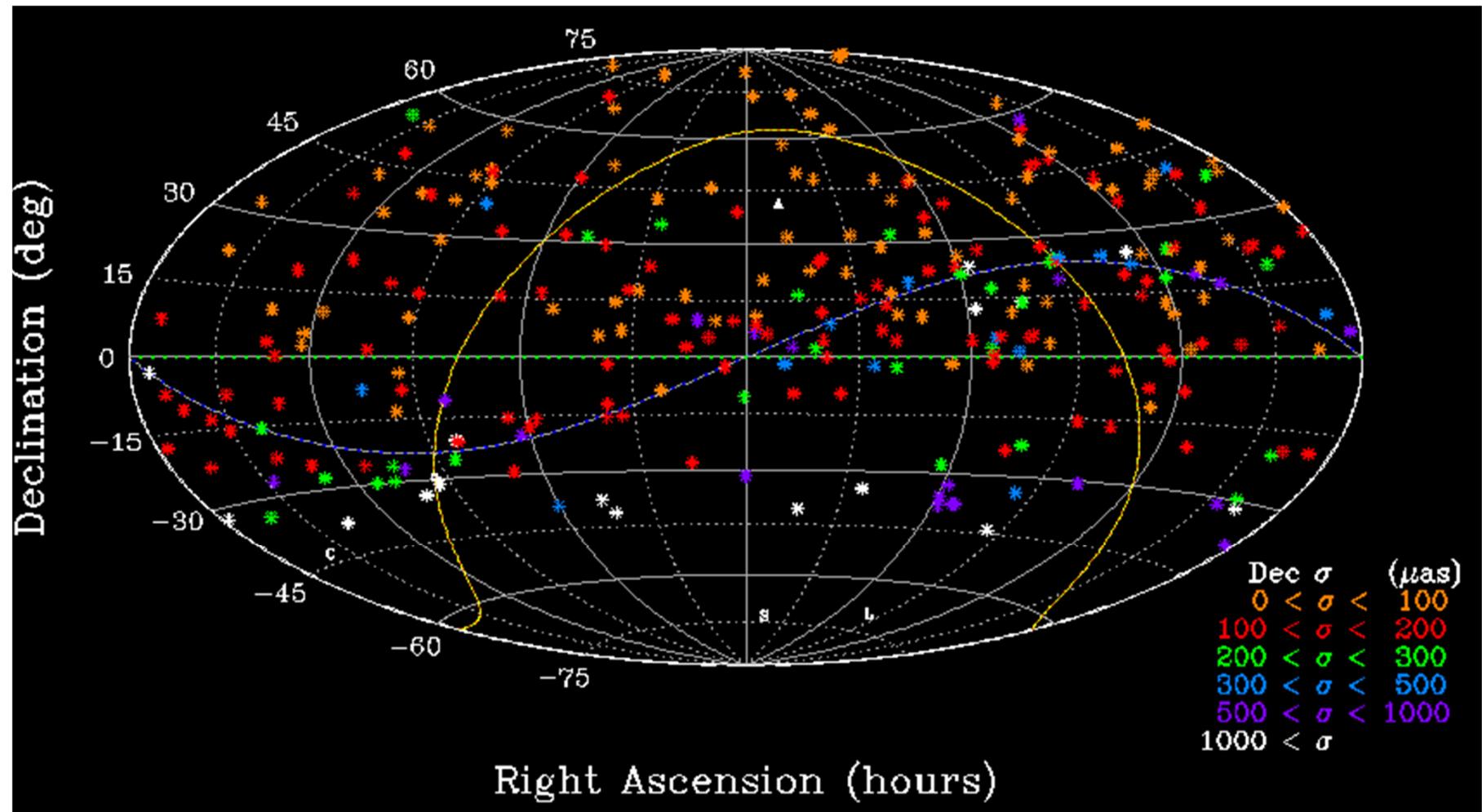
# ICRF2 S/X 3.6cm: 3414 sources



40  $\mu$ as floor. ~1200 obj. well observed, ~2000 survey session only



# K-band 1.2cm: 278 Sources

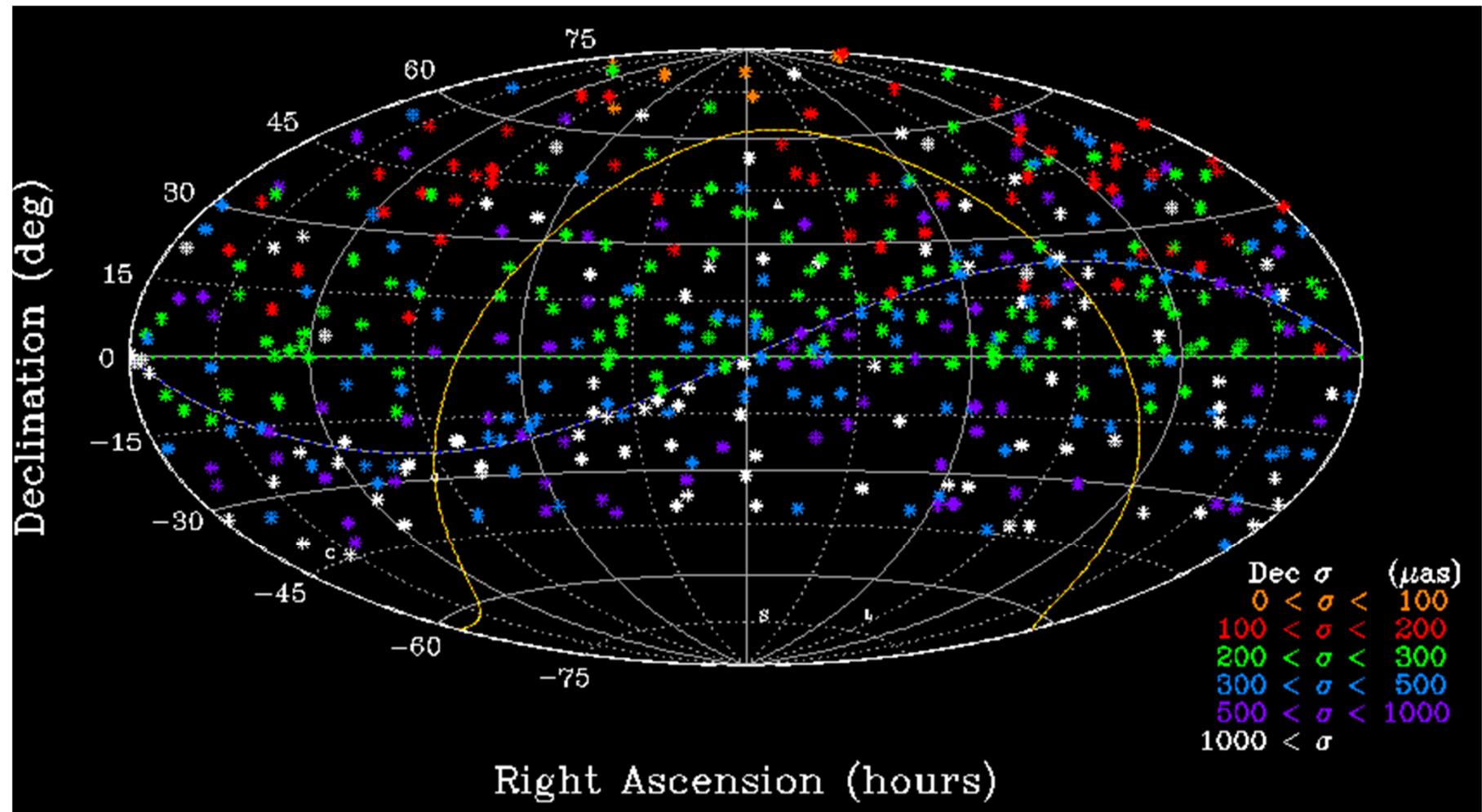


VLBA all northern, poor below Dec. -30°. ΔDec vs. Dec tilt = 500 μas

Credit: Lanyi et al, AJ, 139, 5, 2010; Charlot et al, AJ, 139, 5, 2010



# X/Ka current results: 455 Sources



Cal. to Madrid, Cal. to Australia. Weakens southward. No  $\Delta\text{Dec}$  tilt

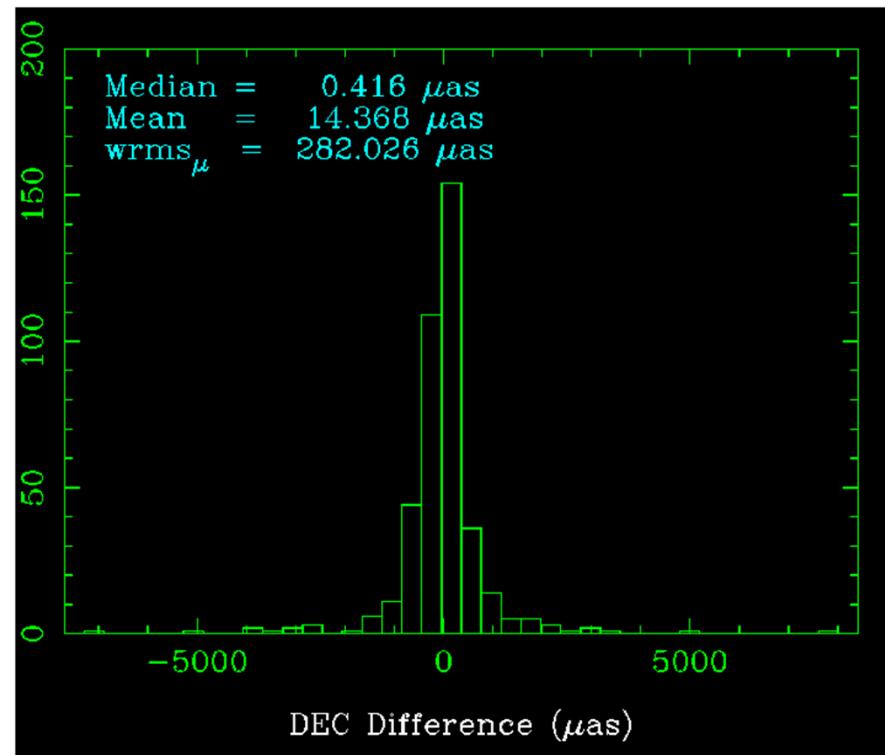
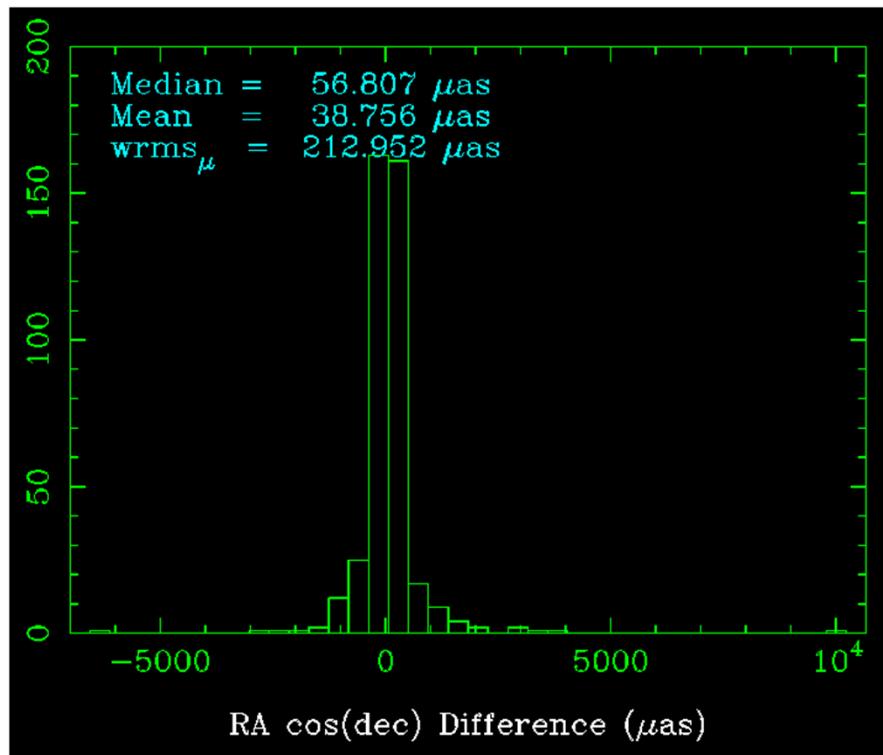
Credit: Jacobs et al, EVGA, Bonn, Germany, 2011



# 9mm (X/Ka) vs. ICRF2 at 3.6cm (S/X)



Accuracy of 404 X/Ka sources vs. S/X ICRF2 (current IAU standard)



RA: 213 μas = 1.0 nrad

Dec: 282 μas = 1.4 nrad

Credit: X/Ka: Jacobs et al, EVGA, Bonn, Germany, 2011  
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009

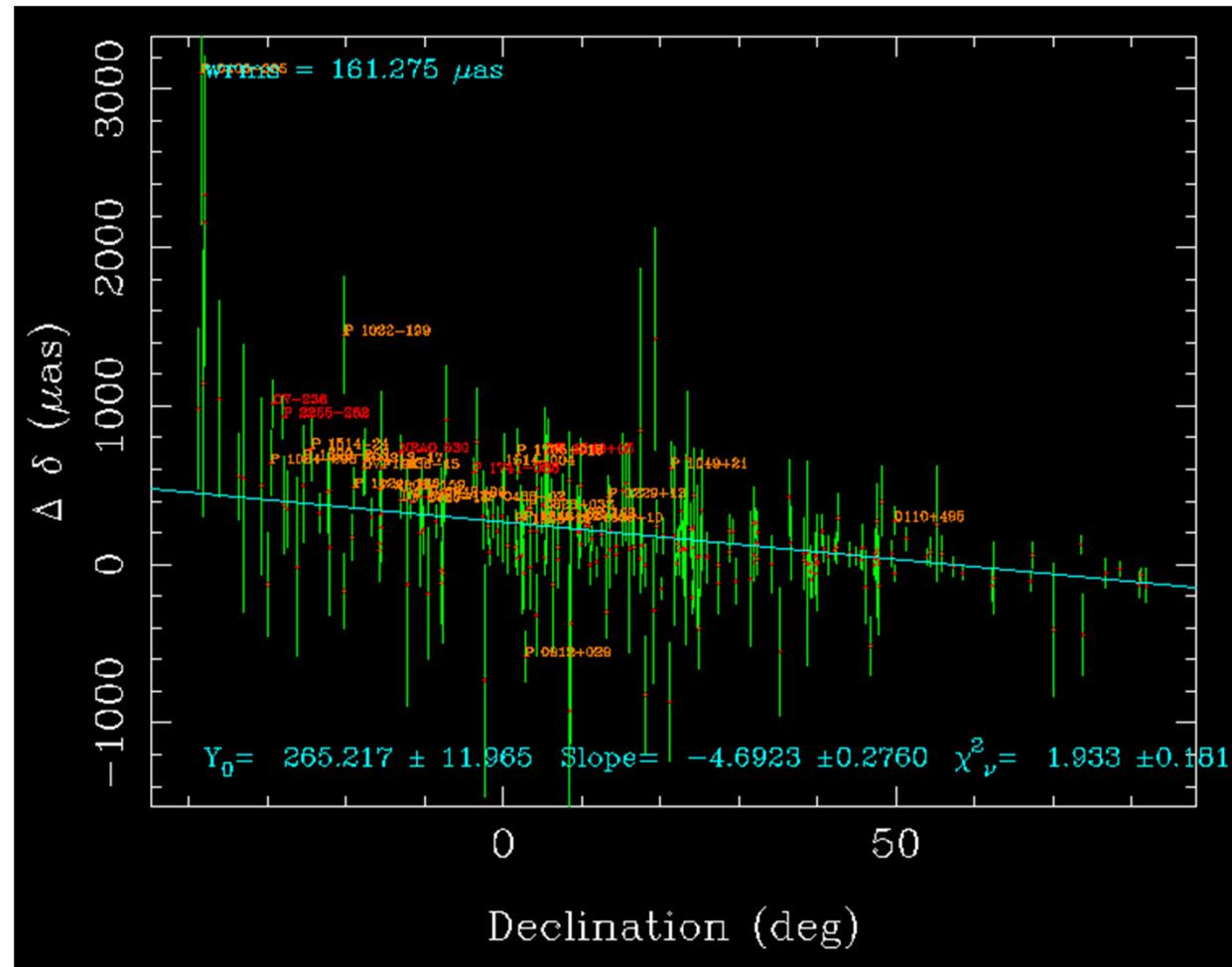


# K-band 1.2cm vs. ICRF2 at 3.6cm (S/X)



Lack of direct  
Dual-band ion  
Calibrations  
*and*  
Lack of any  
Station in south

Leads to poor  
 $\Delta$ Dec vs. Dec  
Zonal stability:  
500  $\mu$ as tilt



## K(1.2cm) Declinations vs. S/X ICRF2 (current IAU standard)

Credit: K(1.2cm): Lanyi et al, AJ, 139, 5, 2010

S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009



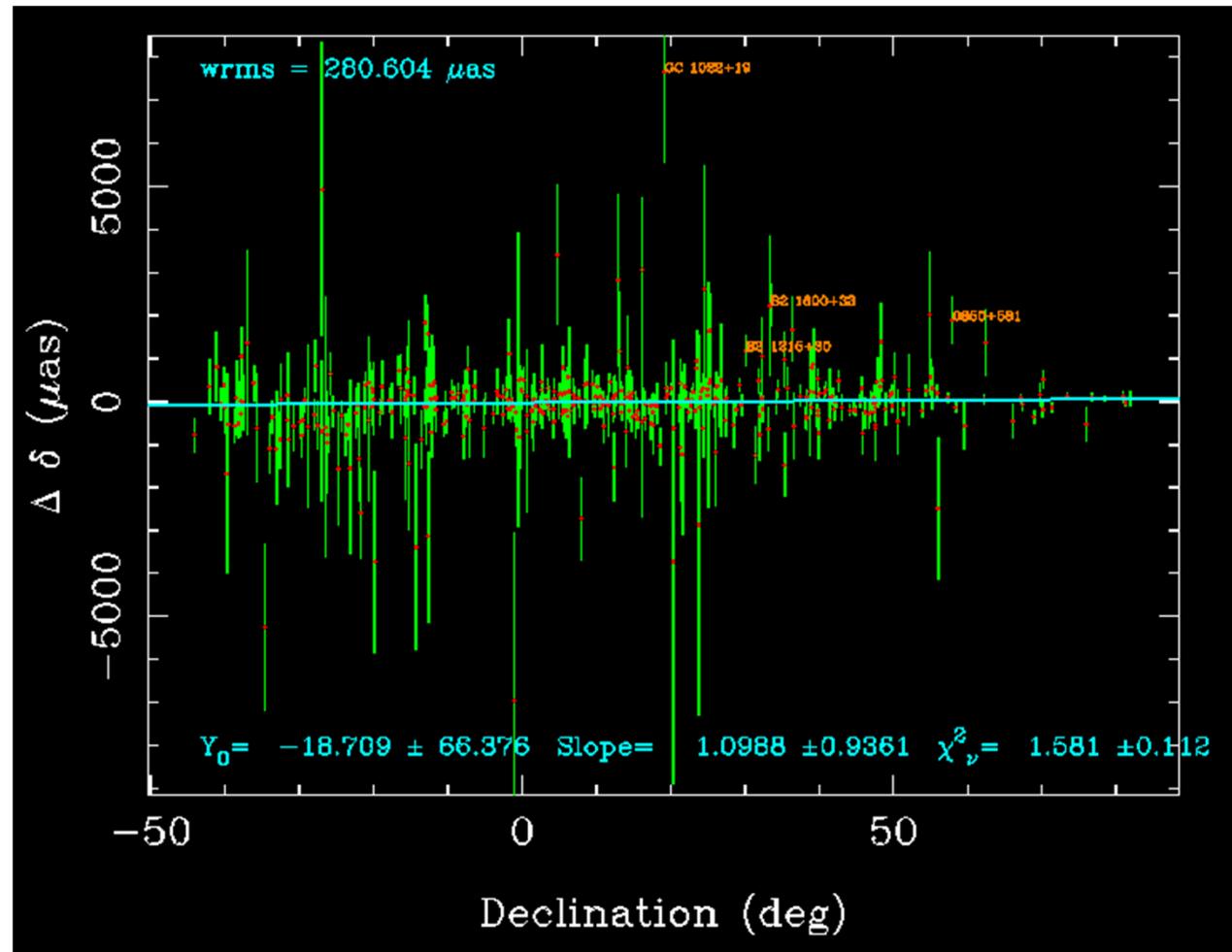
# 9mm (X/Ka) vs. ICRF2 at 3.6cm (S/X)



Dual-band ion  
Calibrations  
*and*  
Station in south

Leads to better  
 $\Delta$ Dec vs. Dec  
Zonal stability:

100+-100  $\mu$ as tilt



## X/Ka(9mm) Dec. vs. S/X ICRF2 (current IAU standard)

Credit: X/Ka(9mm): Jacobs et al, EVGA, Bonn, Germany, 2011  
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009



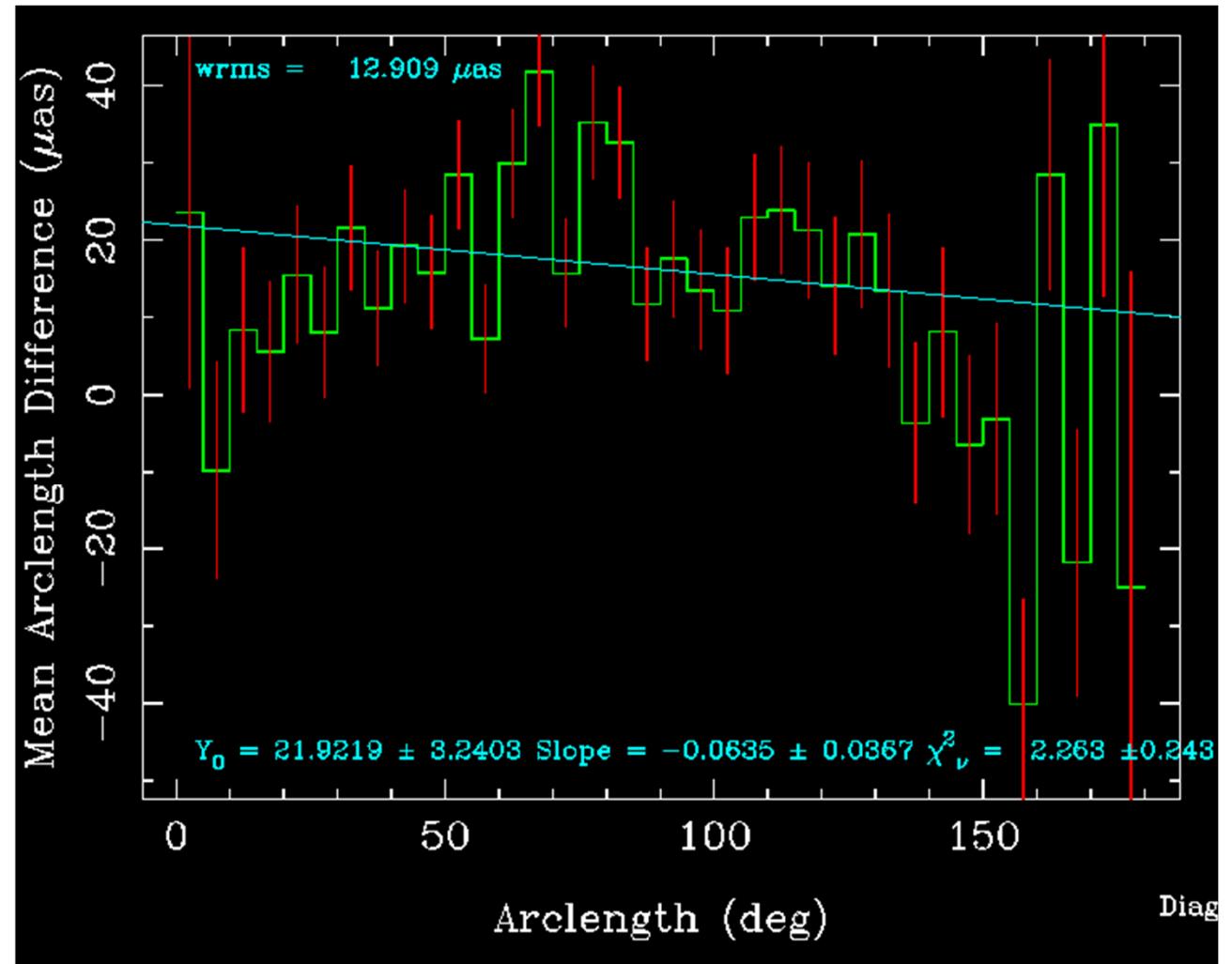
# 9mm (X/Ka) vs. ICRF2 at 3.6cm (S/X)



Mean zonal error  
as shown by  
 $\Delta$ arc vs. arc  
 $\sim 20 \mu\text{as}$  (0.1 nrad)

When southern  
Station XYZ is  
fixed to S/X data  
estimate  $\pm 1\text{cm}$ .

Weaker constraint  
leads to  $150 \mu\text{as}$   
Zonal errors.



X/Ka(9mm) vs. S/X ICRF2 (current IAU standard)

Credit: X/Ka(9mm): Jacobs et al, EVGA, Bonn, Germany, 2011  
S/X ICRF2: Ma et al, editors: Fey, Gordon & Jacobs, 2009



# Improving X/Ka VLBI



## Systems Analysis shows dominant Errors are

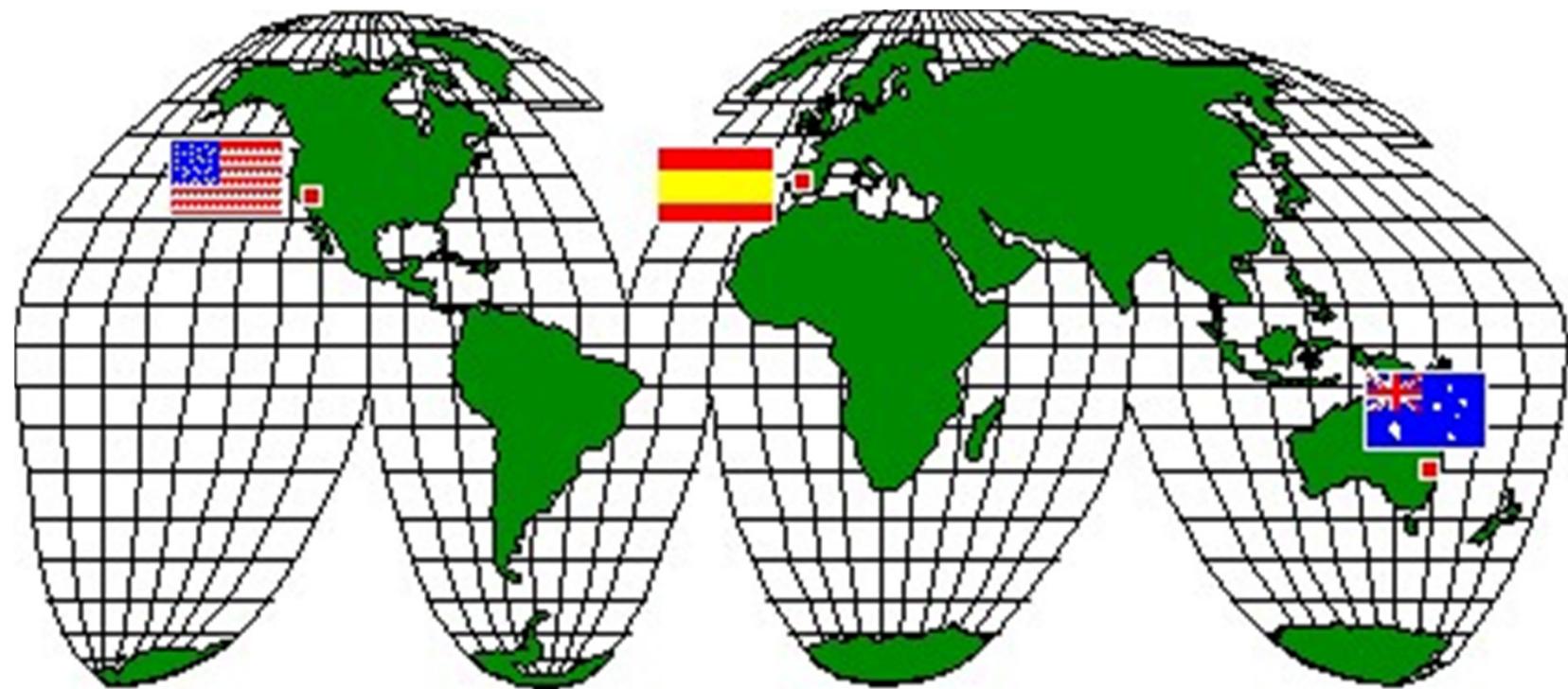
- Limited SNR/sensitivity
  - already increasing bit rates: 112 to 448 Mbps. Soon to 896?
- Instrumentation: already building better hardware
  - Ka-band phase calibrators, Digital Back Ends (filters)
- Troposphere: better calibrations being explored
  - for turbulent variations in signal delay
- **Weak geometry in Southern hemisphere**
  - Limits accuracy to about 1 nrad (200  $\mu$ as) level in Declination
  - No observations below Declination of -45 Deg!
  - DSN has only one southern site: Canberra, Australia (DSS 34)
  - Need 2nd site in the Southern hemisphere



# Attacking the Error budget

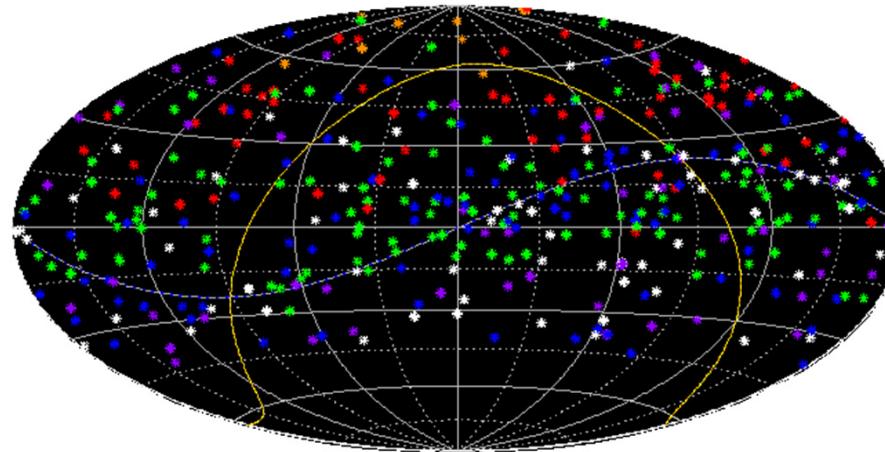


## DSN lack of Southern Geometry



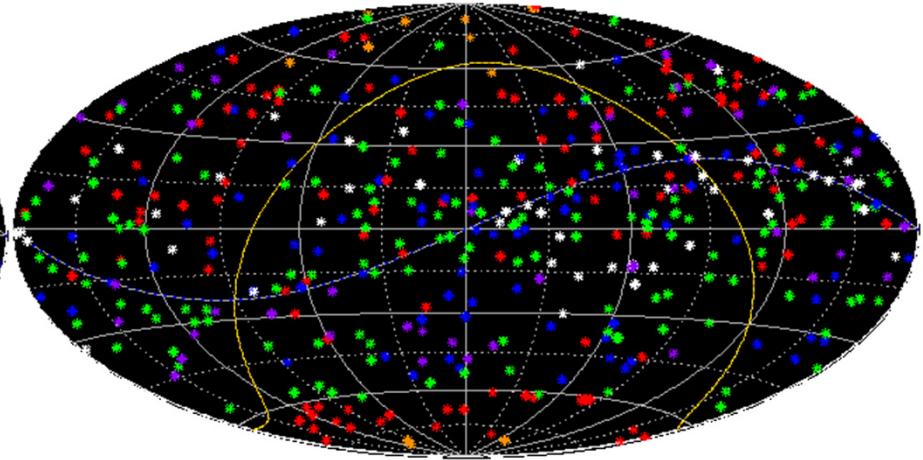


# Simulation of Added Southern Station



*Before Southern Data*

- 50 real X/Ka sessions augmented by simulated data simulate 1000 group delays, SNR = 50  
~9000 km baseline: Australia to S. America or S. Africa
- Completes Declination coverage: cap region -45 to -90 deg 200  $\mu$ as (1 nrad) precision in south polar cap, mid south 200-1000  $\mu$ as, all with just a few days observing.



*After*

Declination Sigma

Orange:	< 100 $\mu$ as
Red:	< 200
Green:	< 300
Blue:	< 500
Purple:	< 1000
White:	> 1000



## Gaia-Optical vs. VLBI-radio:

**Celestial Frame tie  
and  
Accuracy Verification**

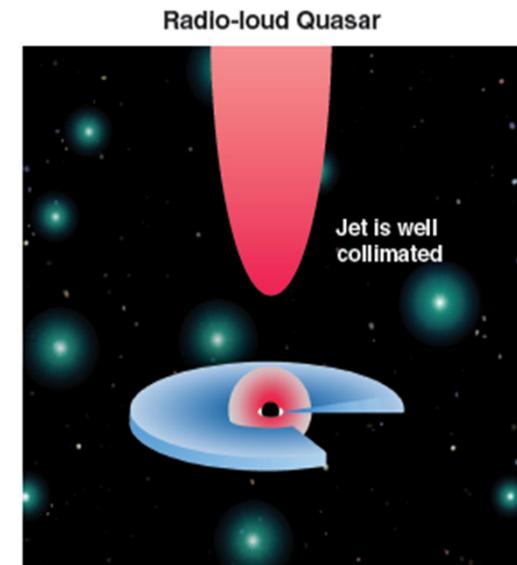
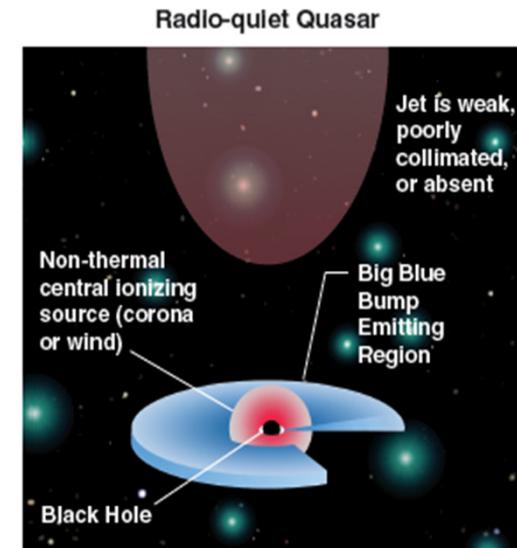


# Optical vs. Radio positions



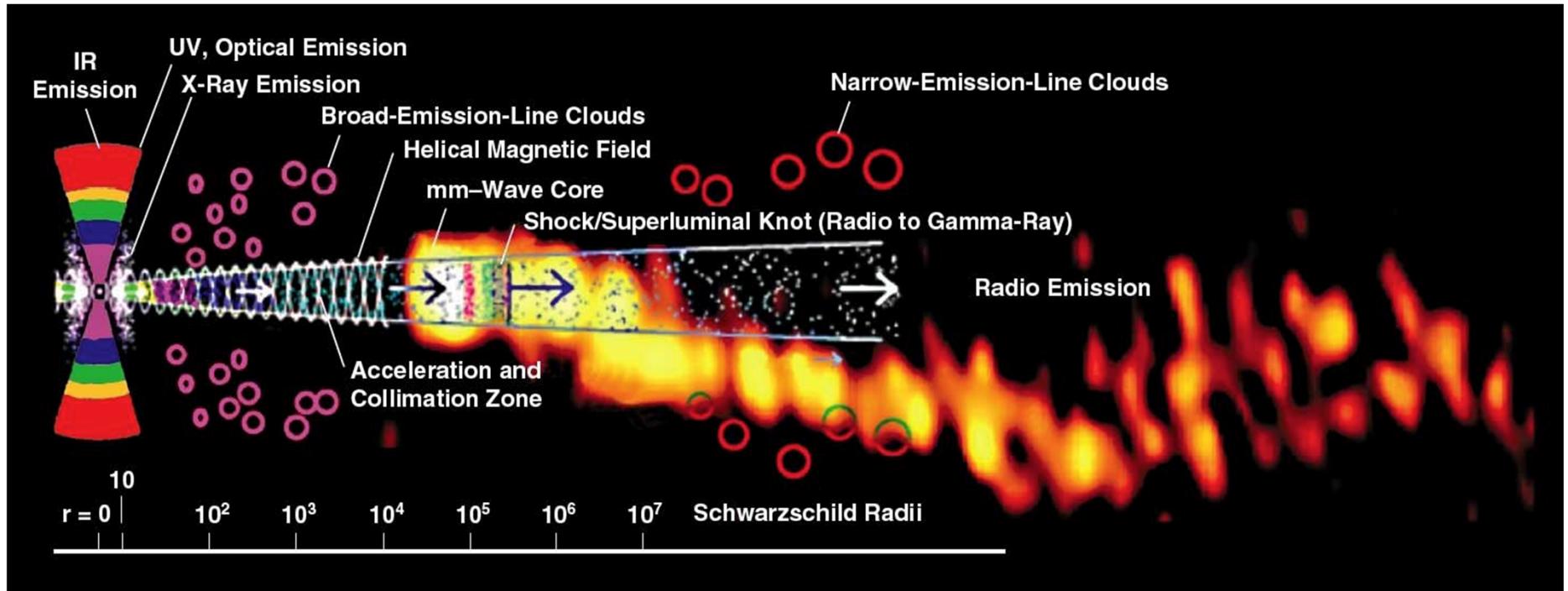
Positions differences from:

- Astrophysics of emission centroids
  - radio: synchrotron from jet
  - optical: synchrotron from jet?  
non-thermal ionization from corona?  
big blue bump from accretion disk?
- Instrumental errors both radio & optical
- Analysis errors





# 9mm vs. 3.6cm? Core shift & structure



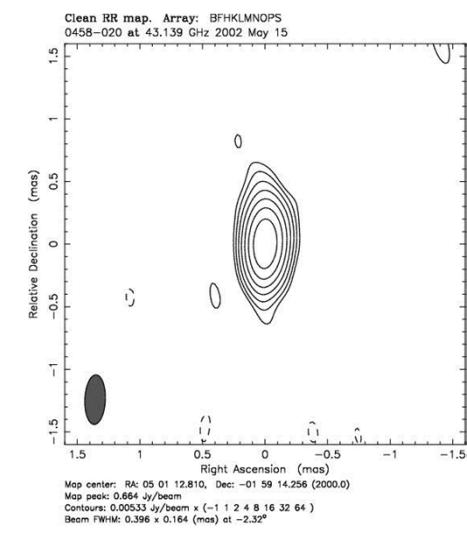
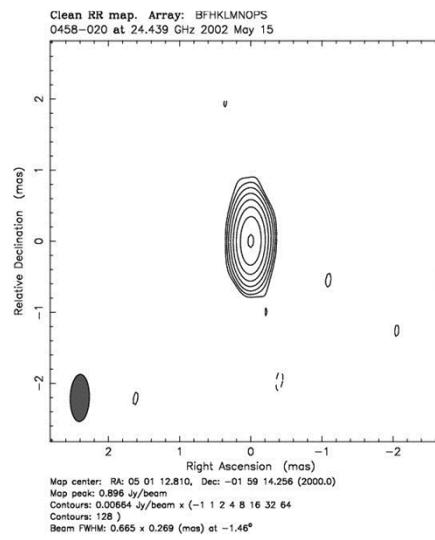
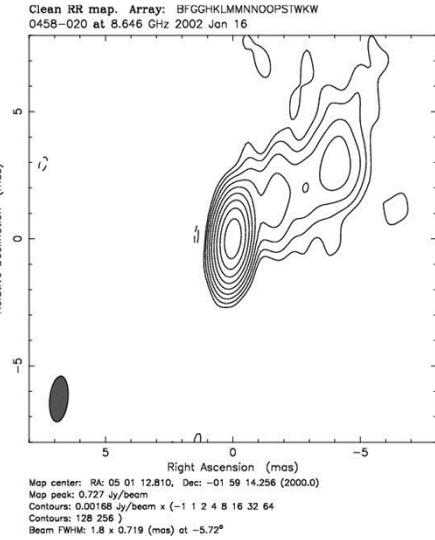
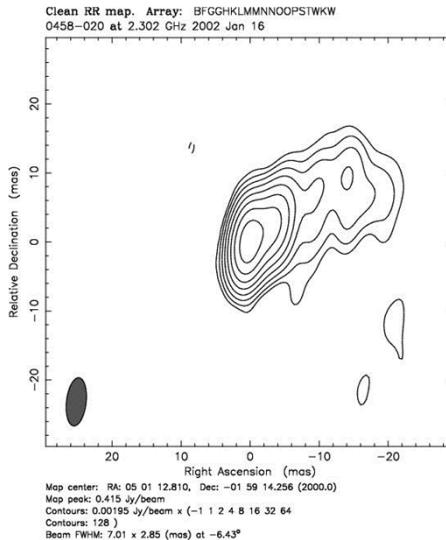
Positions differences from ‘core shift’

Credit: Marscher, 2006. Krichbaum, 1999.

- wavelength dependent shift in radio centroid.
- *3.6cm to 9mm core shift:*  
100  $\mu$ as in phase delay centroid?  
<<100  $\mu$ as in group delay centroid? (Porcas, AA, 505, 1, 2009)
- shorter wavelength closer to Black hole and Optical: 9mm X/Ka better



# Source Structure vs. Wavelength



S-band  
2.3 GHz  
13.6cm

X-band  
8.6 GHz  
3.6cm

K-band  
24 GHz  
1.2cm

Q-band  
43 GHz  
0.7cm



Ka-band  
32 GHz  
0.9cm

The sources become better ----->



# Gaia frame tie and accuracy verification



## Gaia: $10^9$ stars

- 500,000 quasars  $V < 20$   
20,000 quasars  $V < 18$
- radio loud 30-300+ mJy  
*and*  
optically bright:  $V < 18$   
 $\sim 2000$  quasars
- Accuracy  
 $70 \mu\text{as}$  @  $V=18$   
 $25 \mu\text{as}$  @  $V=16$

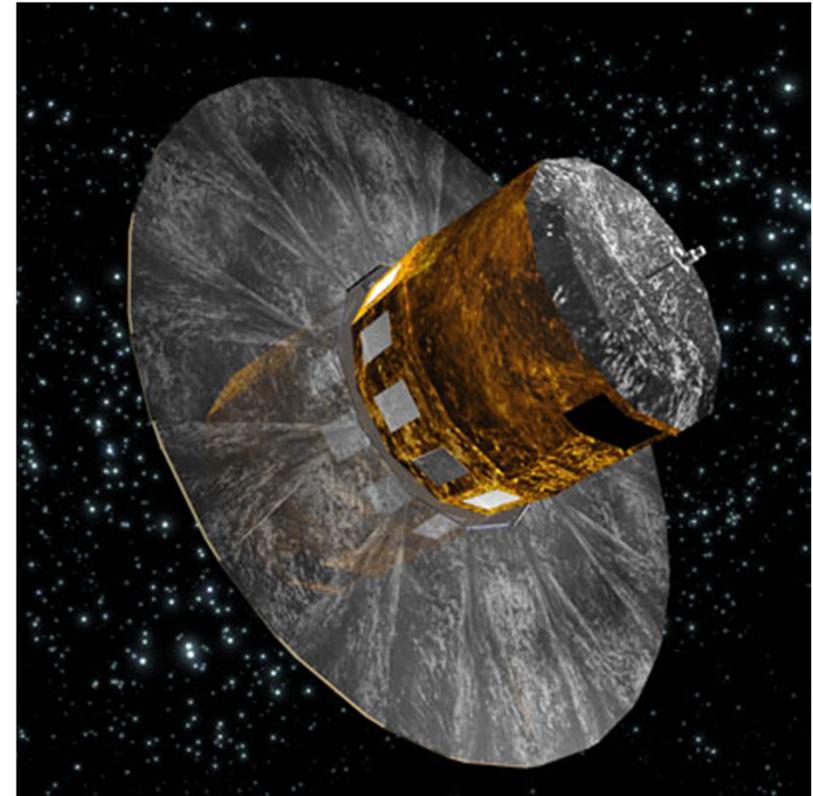
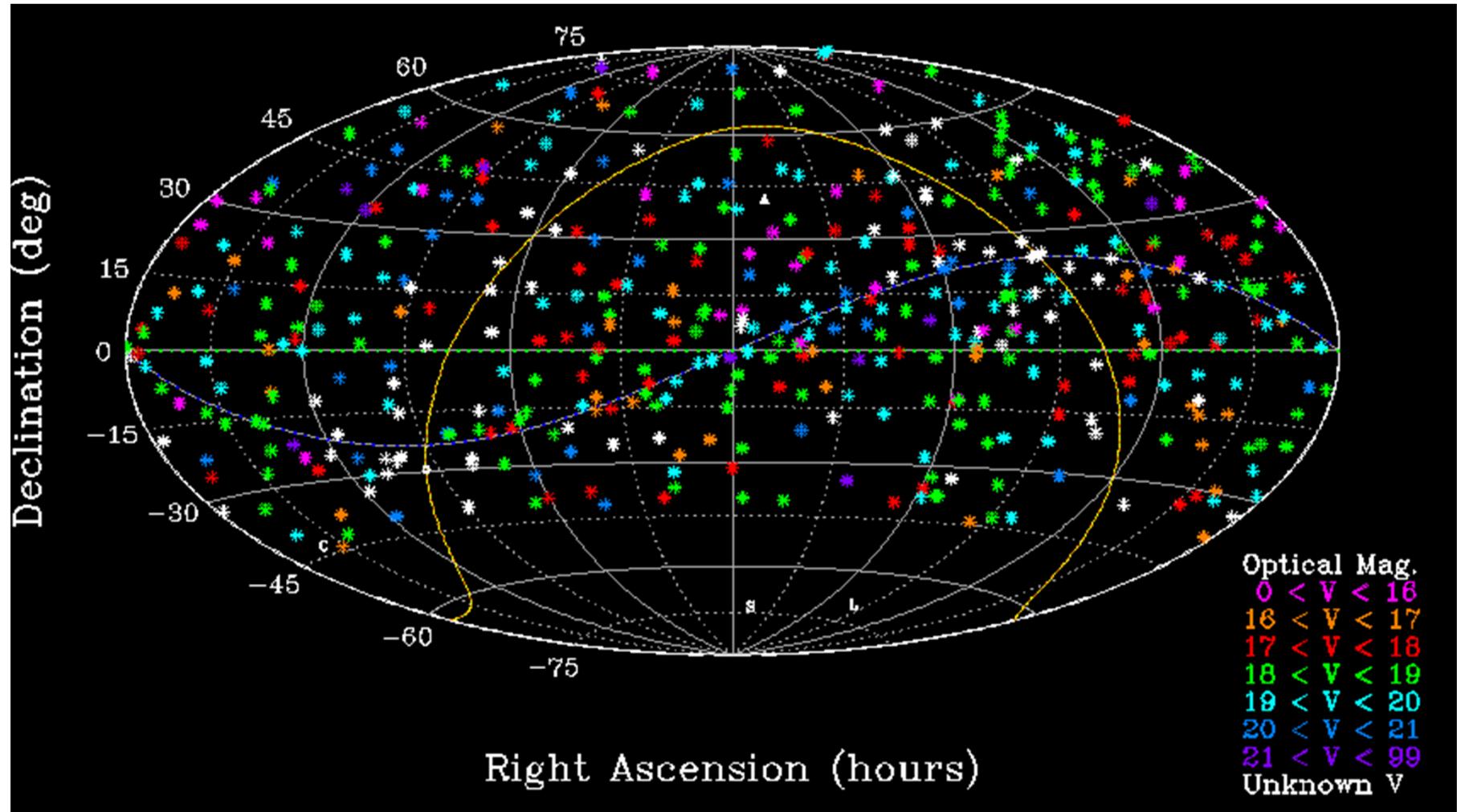


Figure credit: [http://www.esa.int/esaSC/120377\\_index\\_1\\_m.html#subhead7](http://www.esa.int/esaSC/120377_index_1_m.html#subhead7)



# Optical brightness of X/Ka 9mm sources



Median optical magnitude  $V_{\text{med}} = 18.6$  magnitude (*68 obj. no data*)  
 $> 130$  objects optically bright by Gaia standard ( $V < 18$ )



# Gaia Optical vs. X/Ka 9mm frame tie



- 387 of 455 X/Ka 9mm objects with known optical V magnitudes
  - 130 objects optically bright ( $V < 18$ )
  - 206 objects optically weak ( $18 < V < 20$ )
  - 51 objects optically undetectable ( $V > 20$ )
  - 68 objects *no optical info yet* ( $V = ??$ )
- Simulated Gaia measurement errors (sigma RA, Dec)  
for 336 objects: median sigmas  $\sim 100 \mu\text{as}$  per component
- VLBI 9mm radio sigmas  $\sim 200 \mu\text{as}$  per component and improving
- Covariance calculation of 3-D rotational tie  
using current 9mm radio sigmas and simulated Gaia sigmas
  - Rx  $\pm 16 \mu\text{as}$  <- Weak. Needs south polar VLBI (Dec  $< -45^\circ$ )
  - Ry  $\pm 13 \mu\text{as}$
  - Rz  $\pm 11 \mu\text{as}$
- Now limited by radio sigmas for which 2-3X improvement possible.  
Potential for rotation sigmas  $\sim 5 \mu\text{as}$  per frame tie component



# Conclusions



- Astrometry using VLBI at 9mm (32 GHz)  
455 objects: RA, Dec accuracy 200, 280  $\mu$ as
- Quasar astrophysics: 9mm position closer to optical position than S/X-based ICRF2, less extended structure expected
- Need southern *complementary* geometry for  
Full sky radio coverage, 70-100  $\mu$ as accuracy at X/Ka 9mm
- **Gaia tie:**  
>130 objects radio loud *@*9mm *and* optically bright V<18  
Ties Gaia optical to VLBI radio frame  
Study astrophysics: core shift, jet vs. accretion disk  
Independent check on Gaia accuracy at 70-100  $\mu$ as level  
5-15  $\mu$ as potential precision for 3-D frame tie